Modeling Haptic Data Transfer Processes through a Thermal Interface using an Equivalent Electric Circuit Approach

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Abstract: Many activities and scenarios today require human-computer interactions (HCI), and since traditional communication channels such as vision and hearing are often overloaded or irrelevant, there is an increasing interest in haptic interfaces, specifically thermal. Designing and optimizing an effective tactile interface requires an easy-to-use simulation tool to reduce the time for empirical experiments. An original modeling tool was developed in this study to support cutting edge research on human response to thermal stimuli. The human skin tissue model is developed as an equivalent electrical circuit for simultaneous simulation with a thermal display scheme and its control circuitry. The simulator enables monitoring heat flows and temperature variations at any location of the system without intervening in the process itself and inside the skin tissue, for instance, at the depth of the thermoreceptors. The other generic advantage of performing tests with a simulator is the ability to adjust the parameters according to the variety of skin types, test conditions, or thermo-display characteristics, and to simulate the response to different generated stimuli. This report presents the methodology and structure of the model along with an initial empiric validation and suggests directions for further research and future implementation.

1 INTRODUCTION

The human thermal sensory modality offers a novel dimension for transferring information, provided the presented thermal cues are designed in accordance with the sensory system properties. Like other senses, the thermal sense is based on the effect a stimulus has on the sensory system, and its sensitivity to the change that occurred. Therefore, the effect of different properties of thermal stimuli on the sensory system has been studied, and thermal thresholds have been determined. The results show that humans are remarkably sensitive to changes in skin temperature, especially for cooling (Stevens, 1998). For instance, we can resolve a difference of 0.02–0.07°C in the amplitudes of two cooling pulses or 0.03–0.09°C for warming pulses (Smith, 1977), (Kenshalo, 1976). and detect thermal stimuli when skin temperature rises by 0.2°C or descends by 0.11°C (at rates above 0.1°C/sec) (Stevens, 1998), (Ho, 2018). These fundamental properties of the thermal sensory system, and others, provide a framework for defining the optimal characteristics of any thermal stimuli presented to the skin.

Much of the research regarding thermal displays has been focused on their use to simulate the thermal properties of objects in VR scenarios or to facilitate material identification and discrimination based on its typical thermal signature (Jones, 2008). Recent studies have started investigating the feasibility of conveying information via thermal sensation, i.e., using a thermal display to present encoded abstract information, to be sensed and decoded by touch. First steps have been made towards designing suitable thermal cues (Wilson, 2012, 2013), (Singhal, 2015, 2018). The thermal cues must be knowledgeably designed in order to guaranty perceptual distinction with high reliability. There are many challenges in using thermal cues for this purpose, due to the human factor on one hand and technology or experimental factors on the other. Some of the major challenges are the limited and small number of sensations evoked by changes in skin temperature, the multiplicity of parameters that influence the human thermal sensitivity, spatial summation causing poor location

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capability, thermal adaptation, and thermal dynamics of the tissue affecting the human response and hence the sensation, creating the stimuli and monitoring the response. To date, the concept of using a thermal display as a means of transferring data has been established, but the basis for designing the actual cues requires further study regarding the human response to dynamic thermal stimuli.

A haptic thermal interface is a device that excites tactile sensations by relevant thermal stimulation (Nam, 2005). A thermoelectric cooler/heater is very suitable to serve as a thermal interface. It responds fast to variations in the electric driving current and allows the wave-shape forming of thermal haptic signals. It also allows various methods of the drive, including different types of feedback control, such as controlling the temperature of the transmitting surface, the amount of sinking/sourcing heat, and more.

Monitoring skin response to thermal stimuli, throughout the experiments, is necessary for understanding the sources of inefficient identification, and consequently allows stimuli fine-tuning seeking an unambiguous distinction. This issue was illustrated at MIT (Singhal, 2018), (Singhal, 2015), as the skin temperature measured at skin-thermal display interface, while exposed to various types of thermal inputs, indicated that different waveforms such as square waves, sinusoids, and triangular waves resulted in very similar changes in skin temperature, and therefore were unlikely to be perceptually distinguishable. Furthermore, comparing the easiest stimulus to identify (with 100% correct responses across participants), that involved a linear decrease in skin temperature, with the pattern with the lowest percentage of correct responses (64%) that involved a linear increase in temperature from cold to warm, lead the authors to suggest conclusions that can be used as guidelines for designing thermal cues. However, measuring skin temperature at the skin-thermal display interface, is a known challenge. The main difficulties being that the very act of measuring influences the result as it enhances local pressure on the skin and interferes with the heat transfer process, as well as the fact that the layer of the skin relevant for warmth and cold sensation is inherently inaccessible. (Ho, 2017) apparently neglected these influences for her research practical purposes and placed the thermistor at the skin-display interface. Another reported example is (Singhal, 2018) that chose to place a thermistor at the periphery of the contact area of the skin and the display, out of the actual interface area. Both approaches achieving their research goals.

The complicity and the time consumption of these experiments lead us to develop a unique emulator capable of predicting thermal response to various stimuli. The main advantages of this model are that it enables effortless extensive resetting and retesting, as well as 'monitoring' temperature at any chosen point throughout the display - skin array, free of interference in the heat transfer process. Hence, it shall support further research allowing a better understanding of the human thermal sensory processing and enhancing thermal feedback applicability.

A universal model of averaged skin tissue that allows co-simulation with different thermal interfaces can serve as a useful tool for choosing the optimal thermal interface. This method makes it possible to make predictions about parameters in the formation and perception of a tactile signal such as the attack, amplitude, delay, etc. before experimenting with participants.

This paper presents the modeling methodology, the structure of the developed skin-tissue & thermal-display model and an initial empiric validation. Finally, directions for further research and future implementation are suggested.

2 SCIENTIFIC BACKGROUND AND METHODOLOGY

A simplified mathematical model of the skin close to the contact zone was developed, in the form of an equivalent electrical circuit. The advantage of this kind of model is that it can be used to simulate stimulus-response process in conjunction with the electric current driver model using electrical circuits simulation software. In addition, we have developed and built a laboratory system for generating thermal exciting signals (stimuli). The following is a description of the laboratory system, the proposed skin model, and examples of simulating the stimulus-response process in dynamics.

The heat transfer within tissues and the heat transfer in solids can be modeled using an equivalent electrical circuit, as shown in the (Holman, 2002). An equivalent electrical circuit is convenient for joint simulation of thermal processes in tissues and in a thermoelectric module, as well as electrical processes in drivers and control networks. The system of thermo-electrical analogies, where voltage is analogous to temperature and current is analogous to a heat flow, is summarized in the Table 1.

This system of analogies helps to represent a thermal system with distributed parameters as an equivalent electrical circuit with lumped parameters consisting of resistors (equivalent to thermal resistance) and capacitors (equivalent to thermal masses). The initial and boundary conditions of the equivalent circuit are specified as voltage sources (equivalent to a temperature source) and current sources (equivalent to heat sources). The LTSpice program was used in the current study as the environment for simulations. Any other software for electric circuits simulation can be used for this goal as well.

Table 1: Thermo-electrical analogies.

Thermal quantities	Units	Analogues Electrical Quantities	Units
Heat, q	W	Current, I	A
Temperature, T	°C	Voltage, V	V
Thermal resistance, Θ	°C/W	Resistance, R	Ω
Heat capacity, C	J/°C	Capacity, C	F
Common temperature	0°C	Common ground, gnd	0V

2.1 Modeling the Skin Tissue

The surface of human skin is not smooth. The varying degrees of moisture, oiliness, elasticity, hairline, and other parameters make even measurement of the skin surface temperature, nontrivial. Heat distribution under the skin surface is not measurable in vivo.

There are many types of models for thermal processes in tissues. We have chosen the equivalent electrical circuit model type to simulate it together with the model of the thermal signal generator. The basic concept of the presented model is a division of the tissue into submillimeter layers, so that lumped parameters can be used to simulate each layer. Since the overall depth of interest is small, the heat transfer can be considered one-dimensional (Cui, 1990).

Each layer has a thermal resistance ($\Theta, °C \cdot W^{-1}$) and a thermal capacity ($C, J \cdot °C^{-1}$). The values of those parameters can be calculated based on the data in Table 2 and using the following expressions:

$$\Theta_e = \frac{1}{k_e} \cdot \frac{h_e}{A_{cont}} \quad (1)$$

$$\Theta_d = \frac{1}{k_d} \cdot \frac{h_d}{A_{cont}} \quad (2)$$

$$C_e = m_c \cdot c_e = \rho \cdot A_{cont} \cdot h_e \quad (3)$$

$$C_d = m_d \cdot c_d = \rho \cdot A_{cont} \cdot h_d \quad (4)$$

where A_{cont} is the contact area, k and c are thermal properties tabulated in, subscripts "e" and "d" refer to epidermis and dermis respectively, h is the thickness of the corresponding layer.

When building the model, we assume the temperature of the subcutaneous tissue remains unchanged throughout the experiment ($tst \approx 37°C$), due to its low thermal conductivity and since the effect on the skin is performed for a short period of time. Figure 1 shows a schematic visualization of a skin structure using data from (Ratovoson, 2010), (Xu, 2008), and an equivalent circuit model of the fragment of skin close to contact zone. The outer layer of the skin (stratum corneum) is shown at the top of the scheme. The dermis layer of tissue is significantly thicker than the epidermis layer. The temperature of the inner part of the dermis can be assumed as constant stimuli independent (Cui, 1990). The coloured semi-transparent frames show the approximate location of the various receptors responsible for tactile sensations within the skin tissue. The tissue is divided into elements that can be represented as lumped parameters. The mesh resolution was chosen empirically so that increasing the grid resolution does not lead to significant differences in the simulation results. Thus, the epidermis is presented as one element, and the dermis as five identical elements. Each element has its thermal resistance and thermal capacity corresponding to the values of Table 2 and expressions (1)-(4). In normal conditions, the skin is cooled by ambient air. The ambient air temperature is depicted as an equivalent voltage source in Figure 1 (b). The thermal resistance of the convective heat exchange between the skin and the air is shown as an equivalent resistor. As a result, the temperature on the skin surface is about (≈32°C), which is lower than the temperature of subcutaneous tissue. The voltage at point t_r is equivalent to the temperature at the depth of the thermal receptors in kelvin.

Table 2: Skin mechanical and thermal properties (Ratovoson, 2010).

Layer	Thickness, h (m)	Specific heat, C ($J.kg^{-1}.^oC^{-1}$)	Thermal conductivity, k ($W.m^{-1}.^oC^{-1)}$)	Specific mass, ρ ($Kg.m^{-3}$)
Epidermis	0.081m	3590	0.24	1200
Dermis	2m	3300	0.45	1060

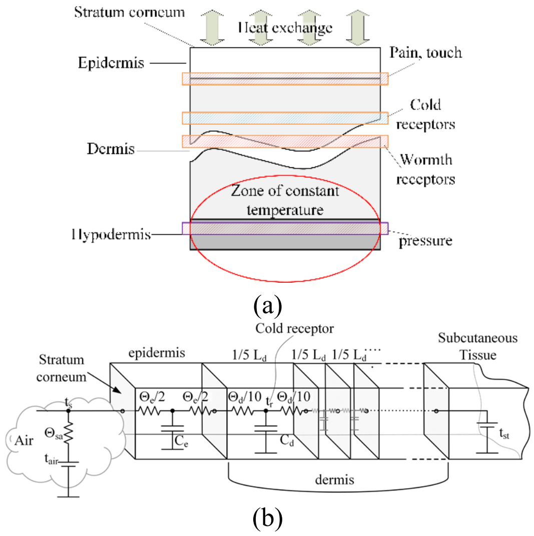

Figure 1: Schematic visualization of the skin structure - (a) Scheme of the fragment of skin based on (Ratovoson, 2010), (Xu, 2008) and (b) Equivalent circuit model of the skin at thermal contact zone based on data from (Gowrishankar, 2004), (Xu, 2008).

2.2 Modeling the Thermal Interface

The laboratory setup is shown schematically in Figure 2(a). The thermostatic hot plate is the substructure of the thermoelectric driver. The temperature of the hot plate is mounted at a constant value of about 40°C using the PID temperature controller. The current-driven solid-state thermoelectric cooler (TEC) is attached with its hot side to the hot plate. Thus, the cold side of the TEC, which is in contact with the skin of the experiment participant, tends to be cooled as the driving current increases. In such a way, the maximum possible temperature of the contact surface is less than 40°C, and the lowest possible temperature value is set to about $5°C$. This is a safe range for test subject at short-time thermal cues. The TEC is thermally insulated laterally using aerogel, and at the cold side using Teflon sheet, except for the contact window, as shown in the Figure 2(a).

The stimuli generator has been tested in the laboratory. It works properly according to design. The primary experiments were carried out with the participation of the researchers. There were just preliminary qualitative measurements without statistical elaboration. The preliminary results are presented below in the corresponding section and do not differ dramatically from the data indicated in the literature.

In a steady-state or quasi-steady-state case, the temperature of the contact surface of the TEC is proportional to the amount of heat pumped from the

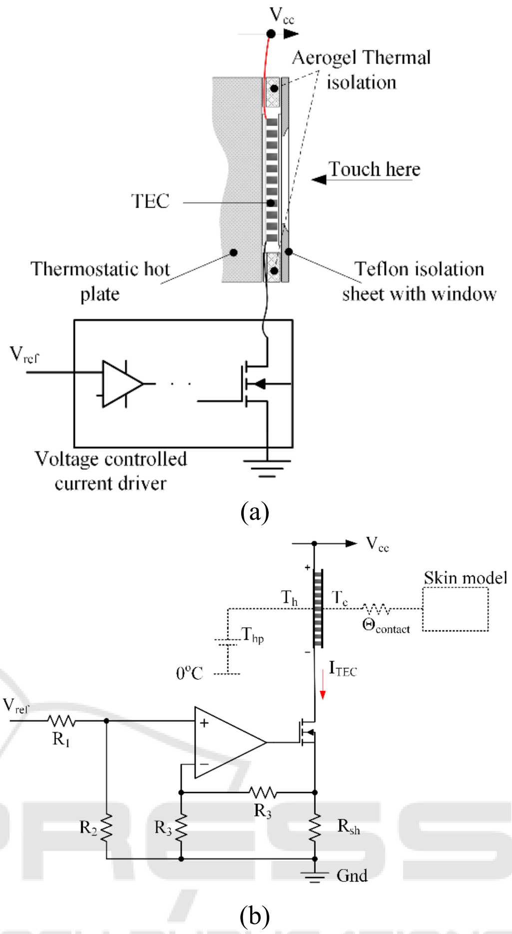

Figure 2: An experimental setup (a) includes the thermoelectric cooler (TEC), thermostatic plate, thermal insulation and a current driver. The circuit for simulation depicted in (b). Solid line represents electrical domain and the dotted line is used for thermal domain. V and I represent voltage and current correspondently, T is the temperature in °C, Θ is the thermal resistance of convective heat transfer. The subscripts ref, hp, h, amb, sa, contact and c refer to reference, hot plate, hot surface, ambient, skin-to-air, contact, and cold surface respectively. The model of TEC is taken from (Lineykin, 2007), the model of skin is shown in Figure 1.

surface by the TEC. The amount of heat sourced or sunk from/to the surface at constant temperature is proportional to the current flowing through the TEC, so it can be easily controlled. At the same time, during transients, a significant part of the heat goes to heating the cooler itself, which has some heat capacity. In order to study the thermal transients and in order to create temperature excitation signals of the desired shape, we used a model of a thermoelectric cooler, developed in early research and published in (Lineykin, 2007). This model can be easily simulated using a circuit simulator such as LTSpice together with electrical driver circuitry.

Equivalent circuit model of the TEC has two electrical terminals ("+" and "-") and two terminals in thermal domain ("Th" and "Tc"), as shown in Figure 2(b). The system of thermo-electrical analogies, where voltage is analogous to temperature and current is analogous to a heat flow, is summarized in the Table 1.

Figure 2(b) depicts the simulation circuit of the laboratory setup. The electrical part of the circuit is a voltage-controlled current source (Trans-admittance amplifier). Resistors R_1, R_2, and R_{sh} are selected in such a way to provide the trans-admittance gain of 0.1 (A/V). In the figure, the thermal interface system is loaded by human skin model in thermal domain. The contact thermal resistance is shown as $\Theta_{contact}$. The principle of skin modeling is explained above.

As an example, let us simulate the effect on the skin of a thermal signal having a relatively standard pattern with a trapeze-shaped cooling wave, as shown in Figure 3. This shape refers to the desired curve describing temperature change of the skin surface vs. time, in response to a corresponding thermal excitation signal. We have designed the shape of the necessary electrical exciting signal, that when applied to the TEC will produce the corresponding thermal signal that is predicted to cause the desired skin temperature change at the contact zone. The result of the simulation of the process of excitation and reaction is shown in Figure 3.

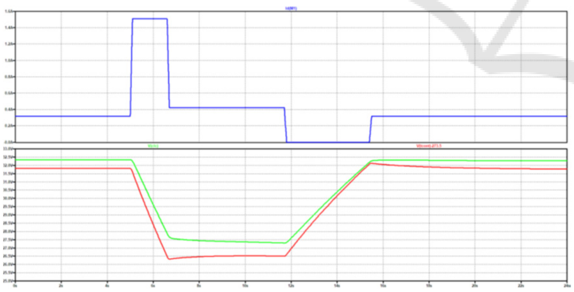

Figure 3: Example of simulating the temperature of skin exposed to a cold pulse thermal excitation. The upper waveform represents the TEC current vs. time. The lower curves show the temperature (1 Vcorresponds to 1°C) vs. time. The green curve shows the skin surface temperature at the contact zone. The red curve shows the temperature of the thermo-display (TEC) under the skin.

3 EXPERIMENTAL VALIDATION

To validate the emulating model, and prove its reliability and precision, we shall refer to previously explored pattern-based thermal icons. For the sake of simplicity and clarity, we chose to focus on one of six basic patterns reported by (Singhal, 2018): *a cooling step*, i.e, an 8 seconds sequence initiating at steady normal skin temperature, a sudden reduction of 6°C @ 3°C/sec rate of change (ROC), followed by temperature maintenance, and return to baseline @3°C/sec ROC.

3.1 Method

The characteristics of the specific thermoelectric Peltier element used by the authors of (Singhal, 2018), were entered into the emulator, and a similar thermal pattern was reproduced. The output simulated thermal cutaneous response, was then observed in comparison to the reported empirical data. To complete the validation process the electrical input required to produce the simulated designated thermal cue, was retrieved and applied to an experimental thermal display setup in our laboratory. The resulting skin and display temperatures were observed in comparison to the corresponding simulated data.

3.2 Results

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3.2.1 Comparison to Reported Data

The thermal display used in prof. Jones' laboratory (Singhal, 2018, 2015) was composed of a thermoelectric cooler model TE-127-1.0-2.5, TE Technology, Inc. 30mm in length and width, attached to a heat sink. Three monitoring thermistors were mounted on the system; thermistor #1 on the surface of the thermal display (used for feedback control) indicating the thermal patterned display temperature change, thermistor #2 on the skin at the edge of the contact area with the display indicating the skin response to the thermal stimulus, and #3 on the skin distanced from the contact area indicating the baseline skin temperature. Similarly, the simulated temperature was sampled at two locations in the model; by the TEC and at the TEC-skin contact point. Figure 4 visually shows the correlation between the simulated skin response thermal and the reported empiric skin response to a chosen stimulus.

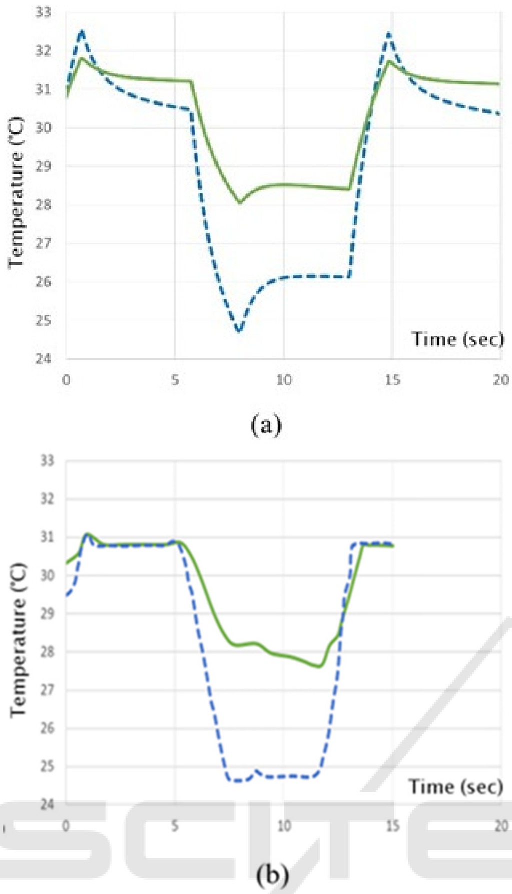

Figure 4: Comparison between simulated and reported signals - (a) Temperatures simulated at skin-display interface (green, solid) and at the display (blue, dashed), (b) Temperature measured by thermistor#2 on skin at the edge of the display (green, solid) and by thermistor #1 on the display (blue, dashed), in response to a cooling step stimulus.

3.2.2 Empirical Evaluation

The electric stimulus, i, e. the electric signal that produced the designated thermal pattern, was retrieved from the emulator and applied to an experimental thermal display setup in our laboratory. The outcoming thermal stimulus was presented to the thenar eminence, as the examinee placed a hand on it and waited for a 2 minute thermal adaptation period. The temperature was measured at three points using three thermistors. Thermistor # 1 was placed directly on the display with a layer of aerogel thermally isolating it from the skin, indicating the thermal display temperature change, thermistor #2 was placed directly on the display with no isolating material making direct contact with the display and with the skin, and indicating skin temperature at interface zone, and thermistor #3 was isolated from the display and in contact with the skin, as shown in Figure 5. The temperatures obtained were recorded and compared with the corresponding simulation data, see Figure 6..

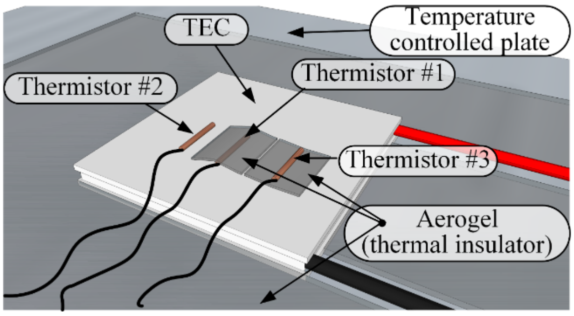

Figure 5: Scheme of experimental thermo-display and monitoring thermistors' layout.

The goal of the experimental measurements at this stage was to prove the proper operation of the thermal display and the correlation between laboratory measurement and simulation results. The experiment did not involve a group of participants. The researchers themselves were the test subjects. In this study, one of many examples is demonstrated that illustrates the correlation between simulation results and laboratory measurements.

4 DISCUSSION

The example of a cooling step brought herein, together with similar results from the evaluation process conducted for other patterns as well, clearly indicates that the presented simulating model stood up to the expectations.

The emulator predicts cutaneous response to a given evoking thermal stimulus, and enables sampling the temperature at any desired location without intervening in the heat transfer process. It also enables deriving corresponding electrical stimulus or predicting thermal response to a given electrical stimulus. Finally, it allows for adjustments to be made throughout testing, in any parameter of the thermodisplay-skin system, in a simple and convenient manner.

Observing the simulated thermal response vs. the reference reported empiric one (Figure 4) shows that the correlation between them is not perfect. Whereas for the reported experiment results, the curve indicating the display temperature change is a well-shaped symmetrical step as predetermined, and the curve indicating the skin temperature is somewhat a distorted step, for the simulated output, it is vice versa. The reason the reported data is such is due to the experiment description defining the display temperature as the controlling parameter. Another iteration with the emulator would have produced a better correlation, but we specifically chose to strive for the skin temperature curve to be the well-shaped step, because that is the more relevant parameter for thermal sensation. The thermal cue is actually not the displayed temperature change, but rather the change sensed by the skin.

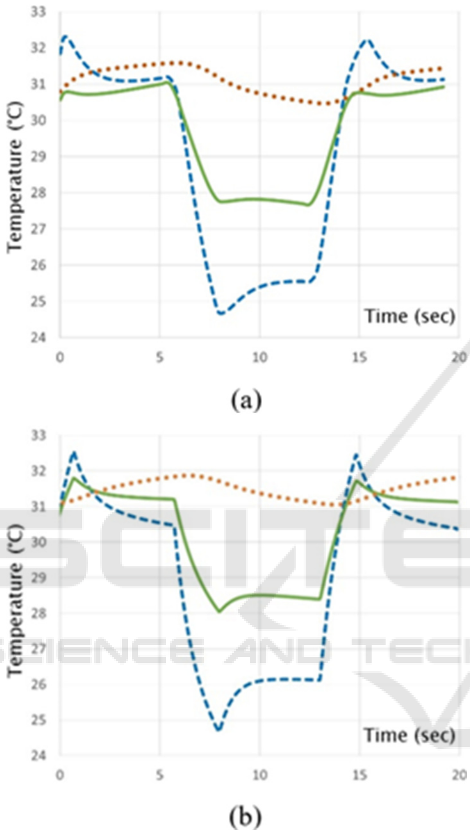

Figure 6: Comparison between measured and simulated signals: (a) Temperatures measured by thermistor #2 at the skin-display interface (green, solid), by thermistor #1 on the display with isolation from the skin (blue, dashed) and by thermistor #3 on the skin with isolation from the display (brown, doted) all in response to the cooling step stimulus, (b) Temperatures simulated at skin-display interface (green, solid), at the display (blue, dashed) and inside the dermis layer (brown, doted).

The locations of the monitoring thermistors reveal a difference between the reference reported experiments and the experiment described herein. The thermistor monitoring the display temperature (marked #1) was mounted the same way, i.e. at the contact zone with isolation from the skin. The reported thermistor #2 was used to measure the skin temperature, and was attached to the skin at the edge of the contact zone. Whereas we chose to place the second thermistor adjacent to the first one at the contact zone, only without any isolating material, as it was meant to monitor the temperature at skin-display interface. The different approach was mainly for practical reasons, and may have a slight quantitative influence on the magnitude of the temperature change, but should not have any qualitative impact on the shape of the curve. The different technical approaches demonstrate part of the challenges involved in conducting haptic thermal sensing experiments, many of which may be avoided by the presented emulator.

The thermal sense is based on the effect a stimulus has on the sensory system and its sensitivity to the change that occurred. It is important to emphasize that the actual effect on the skin is the resultant of the heat transfer process that occurs between the thermal display and the skin following a thermal stimulus. The heat flow depends not only on the stimulus but also upon the thermal characteristics of the elements involved in the interaction, namely the display, the skin, and the thermal resistance of the contact at the interface between them. The contact resistance is derived from many parameters other than the material's thermal resistance, e.g, the contact area, quality of contact due to surface roughness, pressure etc. All these parameters are simulated by the presented model with electrical elements and can easily be controlled and adjusted, representing various people, skin conditions, locations on the body, etc. as well as contact conditions.

When investigating the haptic thermal sense in the context of data transferring capabilities, the main issue is the recognizability of the thermal cues. Although temperature monitoring on the surface of the skin throughout the heat transfer process, provides essential data for understanding the process, however, the ability to distinguish between cues and recognize them, derives from the temperature changes that the thermoreceptors are exposed to, combined of course with the psychophysical aspects that ultimately determine the thermal sensation. Actually, at the biochemical level the receptors really respond to the temporal absolute temperature (by firing action potentials at frequencies in accordance to the temperature), however, since the thermo-sensation is the outcome of the combined warmth and cool thermoreceptor's transmissions together with the adaptation phenomena (at temperatures of 30-36°C) and other neural and cognitive analysis, at the functional level *the sensory system responds to changes in cutaneous temperature*. The temperature change that occurs inside the dermis layer at the depths of the cold and warmth thermoreceptors, is determined by the rate of heat flow initiated by stimulus at the skin-display interface. Under normal steady-state conditions of body core temperature (approx. 37°C) and skin surface temperature (approx. 32°C), a natural heat flow constantly occurs due to the temperature gradient, resulting in, and balanced by, body heat emitting off the skin. Once skin surface is evoked by the thermal cue, heat flow changes accordingly. A cooling pulse increases the temperature drop, hence the rate of heat flow pumped out of the body through the skin. A warm pulse only decreases the total heat flow but the local and temporal response involves a change of direction. To conclude this remark, the *absolute* temperature on the skin surface does not reveal the thermal sensation, whereas the temperature *change* at the thermoreceptors does indicate the sensation. The presented emulator will allow exploring the possibility that the heat flow, simulated by electrical current, can predict the sensation perhaps even with greater reliability than temperature change.

As mentioned in the description of the experiment, a third thermistor (marked #3) was placed at the skin-display contact zone but with thermal isolation from the display (see Figure 5). This was in an attempt to capture the skin response without the display temperature distorting the measurement. However, in practice, this caused not only the thermistor to be isolated from the display, but also a significant area of the skin was isolated from it, thereby distancing it from the heat flow between the display and the skin. This distance dramatically flattened the temperature curve, due to cutaneous thermal resistance, as shown in Figure 6(a). It is interesting to notice the resembling behavior to the simulated temperature curve sampled inside the dermis layer, indicating the cutaneous response sensed by the thermoreceptors, as shown in Figure 6(b). In other words, this preliminary finding insinuates that a distance on the surface of the skin may perhaps represent the inaccessible depth, for practical experimental purposes. Another application could be using the simulated temperature change sensed by the thermoreceptors, to design thermal cues. This obviously requires empirically characterizing criteria for recognizable thermal changes. In a more general view, this finding is just an example of the potential contribution the emulator may have to advance further research.

It shall be noted that the amplitude of the temperature change by the thermoreceptors, is approximately 1°C @ rate of change (ROC) of approximately 0.2°C/sec. This value is substantially greater than the human threshold, as detailed above (see introduction), supporting the fact that the thermal cue was well noticed by experiment participants.

Known design limitation: The temporal processing of the human thermal sense, has a great impact on the ability to design thermal displays, but at this stage is not simulated or in any way reflected by the presented model. This is especially significant when cues include both warm and cool stimuli, as explained hereinafter. The response time to thermal stimuli was found to differ between cold and warm stimuli, with a more rapid response to the cold stimuli (0.3-0.5 sec for ROC greater than 0.1°C/sec) than warm stimuli (0.5-0.9 sec) (Ho, 2018), (Nam, 2005). This finding is consistent with the biological structure and biochemical function of the thermal sensory system, with warmth thermoreceptors located deeper in the dermis in comparison to cool thermoreceptors (0.3 vs. 0.15 mm) hence, heat transfer initiated at the interface on skin surface is detectable with delay, and the different types of nerve fibers innervated by the receptors cause a conduction velocity difference in an order of magnitude (0.5-2 vs. 3-30 m/sec). Ho et al. (Ho, 2017) investigated the physical-perceptual correspondence of dynamic thermal stimuli. They showed that for warm stimulation, as expected, subjective sensation always comes after the corresponding physical event (change in skin temperature), in respect to onset and to peak. Whereas for cold stimulation, although the subjective onset always follows the physical onset (with smaller delay than the response to warm onset), the sensation of cooling peak is accelerated to an extent that it can even precede the physical temperature peak temperature. They concluded that the sense of cold is more transient than the sense of warmth, therefore responds more readily to transient changes (dT/dt). If necessary, this issue will be addressed in the future.

5 CONCLUSIONS

The presented equivalent circuit-based simulator was developed in light of scientific knowledge available to date that is based on decades of research in the different relevant disciplines. The model simulates heat transfer processes in thermodisplay-skin interactions, and provides a generic capability that can potentially be used to advance R&D in this unique and promising field of interest. The simulator has been validated via several tests and experiments. The main advantages the simulator offers, are the following: The ability to monitor temperature changes during heat transfer processes, at any chosen location without influencing the very process and hence the result, including subcutaneous layers. The ability to conduct extensive tests by readjusting the parameters according to the variety of skin types, test conditions, or thermo-display characteristics, and various stimuli, thereby dramatically reducing the need for actual experiments. In addition, the ability to conveniently determine the electrical stimulus required to produce a designated thermal cue, or alternatively to predict the cutaneous thermal response to a given stimulus.

Implementation in Future Work: The general objective of the research is to develop methods to effectively use the human thermal sense, as a data transfer medium – an alternative or complementary channel for various scenarios in which conventional channels, vision, hearing, and tactile sensing are not applicable or not sufficient (e.g. enhance a communication capability for the deafblind (Korn, 2018), transfer messages in noisy/silent environments). Future study will focus on diversifying the variety of thermal cues suitable to convey information, with two specific goals:

- Create a broad set of recognizable thermal icons – the research will include evaluating a variety of pattern-based structured thermal icons designed in light of the latest reported findings.
- Evaluate new approaches for advanced thermal icons - overcoming inherent human limitations due to special summation and other sensual phenomena.

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